MONAE

Water Framework Directive – Transitional and Coastal Waters
Proposal for the definition of water bodies

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Definition of water bodies in transitional and coastal waters for Portugal

Executive Summary

An approach for the division of transitional and coastal waters in Portugal into water bodies for management and monitoring purposes was developed by a working group drawn from the MONAE team, and is outlined in this document. Two distinct methodologies were used: for the definition of *Open Coastal Water Bodies* literature results were used, and for *Transitional and Restricted Coastal Water Bodies*, a bottom-up data analysis approach was taken.

Figure 1 - Summary of water bodies defined for transitional and coastal waters in Portugal

Types	Water category	Systems	Nº of water bodies
A1 – Mesotidal stratified estuary	Transitional	Minho estuary Lima estuary Douro estuary Leça estuary[1]	5 3 3 -
A2 – Mesotidal well-mixed estuary	Transitional	Ria de Aveiro Mondego estuary Tagus estuary Sado estuary Mira estuary Arade estuary Guadiana estuary	5 3 4 6 3 1 3
A3 – Mesotidal semi-enclosed lagoon	Coastal	Óbidos lagoon Albufeira lagoon St. André lagoon	2 1 1
A4 – Mesotidal shallow lagoon	Coastal	Ria Formosa Ria de Alvor	5 1
A5 – Mesotidal exposed Atlantic coast	Coastal	Open coast	6
A6 – Mesotidal moderately exposed Atlantic coast	Coastal	Open coast	4
A7 – Mesotidal sheltered Atlantic coast	Coastal	Open coast	4
Total			60

[1] The Leça estuary was excluded, since it is classified as an artificial structure (Bettencourt et al, 2003).

There are common points to both methodologies, since in the two cases natural factors such as salinity or morphology are combined with the human dimension, using the significant pressures and/or key elements of state.

The application of these methodologies has resulted in the definition of 60 transitional and coastal water bodies for Portugal, which are detailed in Figure 1.

INTRODUCTION

The main purposes of the Water Framework Directive (WFD) are "to prevent further deterioration of, protect and enhance the status of aquatic ecosystems and the terrestrial ecosystems and wetlands directly depending on them". The WFD Guidance on Monitoring emphasises that "water bodies are the units that will be used for reporting and assessing compliance with the Directive's principal objectives". Article 2.10 of the WFD defines body of surface water as "a discrete and significant element of surface water such as a lake, a reservoir, a stream river or canal, part of a stream, river or canal, a transitional water or a stretch of coastal water". The water body is, according to the WFD Guidance on Monitoring, "a sub-unit in the river basin (district) to which the environmental objectives of the Directive must apply". Water bodies should be defined for the systems classified according to the typology determined by each member state for its own water categories characterization. Figure 2 summarizes the relationship between these definitions.

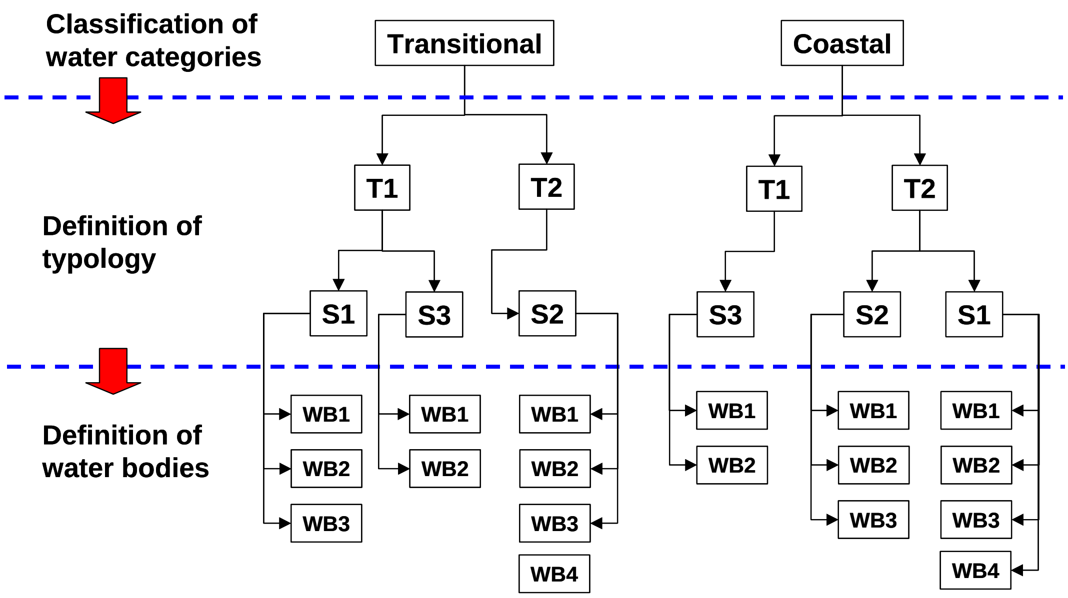

Figure 2. Summary of the elements stipulated in the WFD for definition of water bodies.

The main goal of identifying water bodies is “to enable the status to be accurately described and compared to environmental objectives”. Therefore, “a discrete element of surface water should not contain significant elements of different status since a water body must be capable of being assigned to a single ecological status class using the Directive’s monitoring programmes”. However, and due to logistic burdens, the fragmentation of surface waters into “unmanageable numbers of water bodies should be avoided” and a balance should be attained between the description of the water status and the number of water bodies. The guidance also states that “where there are numerous and significant differences in status the number of water bodies should also be numerous; where the status is similar, water bodies will tend to be larger in size and fewer in number”.

Although the criteria for water body definition should be based initially on geographical and hydrological determinants, the key descriptor is the status of a particular area, which should be considered homogeneous and significantly different from adjacent areas. The identification of the relevant anthropogenic pressures is an additional criterion to be considered for the definition of water bodies, as stated in Annex II of the WFD. For that purpose the identification and estimation of significant point and diffuse pollution from urban, industrial and agricultural uses must be carried out.

The objectives of this work are:

1) To present the methodology used for definition of water bodies in transitional and coastal Portuguese waters;
2) To show the results obtained for water body definition in two well studied systems: a transitional water and a restricted coastal water, in order to validate the methodology;
3) To identify water bodies in all transitional and coastal Portuguese systems greater than 1 km^2 (minimum area recommended in the WFD Guidance on the Common Understanding of Terms) using this methodology.

METHODOLOGY

The methodology described herein is divided into two parts, depending on the typology indicated in Figure 3. The first part applies to open coastal water types (A5,

A6 and A7), and the second to transitional and restricted coastal water types (A1, A2, A3 and A4).

Two systems were selected to test the methodology for transitional and restricted coastal systems, based on the quantity and quality of available data: The Mondego estuary and the Sado estuary.

Figure 3. Portuguese types and systems under study for definition of water bodies.

Types	Water category	Systems
A1 – Mesotidal stratified estuary	Transitional	Minho estuary Lima estuary Douro estuary Leça estuary[2]
A2 – Mesotidal well-mixed estuary	Transitional	Ria de Aveiro Mondego estuary Tagus estuary Sado estuary Mira estuary Arade estuary Guadiana estuary
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A7 – Mesotidal sheltered Atlantic coast	Coastal	Open coast

Open coastal waters

Criteria

The principal criterion proposed for defining *Open Coastal Water Bodies* is the existence of natural morphological accident in the coastline that receives significant freshwater inputs, in conjunction with hydrological regime of the rivers and anthropogenic pressures. This criterion is in line with numerous studies of sediments, physics, biology and contamination in the coastal zone. Profound changes in the

[2] The Leça estuary was excluded, since it is classified as an artificial structure (Bettencourt et al, 2003).

ecology and quality of coastal waters adjoining to major rivers in the world have been reported, and although rivers in Europe are comparatively small, several estuarine systems are contaminated and discharge a mix of contaminants to the adjacent coastal area on a regular basis. Taking into consideration the influence of estuarine systems on the coastal adjacent areas, *Open Coastal Water Bodies* may be classified as follows:

(i) Category A - Coastal water adjacent to estuaries and coastal lagoons with permanent connection to sea that receive significant quantities of freshwater over the whole year, and of anthropogenic discharges from land uses, industrial activities or population centres;

(ii) Category B - Coastal waters from exposed to sheltered regions that show no evidence of being directly substantially influenced by freshwater and suspended solid discharges and by anthropogenic materials.

<u>Approach</u>

According to the WFD the quality of coastal waters should be monitored (for Biological Quality Elements – BQE, and Supporting Quality Elements, SQE) within the first nautical mile measured from the inshore limit of territorial waters – in Portugal, and additional limit of 30 meters depth, if further offshore, has been stipulated. The discharge of some systems influences the quality and ecology of adjacent coastal regions beyond this limit, either on a regular basis or episodically. The procedure proposed to delimit the geographical areas in the coastal zone that are influenced by discharges of transitional waters and associated anthropogenic substances is:

(i) As a first approach, a conservative parameter such as salinity should be used to delimit the area directly influenced by the exchanges between estuarine systems and adjacent coastal waters. Salinity fields in these areas are greatly influenced the water volume exchanged tidally and the river flow regimes. Tidal effects are dominant in macrotidal and mesotidal shallow systems. In general, the freshwater input to estuarine systems, and consequently the export to the adjacent coastal area, varies seasonally due to precipitation. In southern Europe the seasonal signal is stronger as rain is concentrated in short periods during the year (Vale, 1990). *Open Coastal Water Bodies* should be extended further offshore until salinity reaching values that do not differ from those observed in the reference station located at an adjacent *Open Coastal Water Body* of category B. We propose a difference of 0.5 salinity

units to avoid extensive areas for *Open Coastal Water Bodies* strongly influenced by river plumes.

(ii) The suspended particulate matter (SPM) concentration, which is greatly influenced by discharges of macrotidal and mesotidal estuaries to the coastal zone, should also be considered. The intensity and extent of the SPM plume vary with the tidal amplitude, which fluctuates on semi-diurnal and fortnightly scales, and tends to be maximum in periods of high river flows and floods when estuarine suspended load is transported seaward. Strong winds and storm conditions may also increase the SPM concentrations in coastal waters due to bottom resuspension, but those values should not be considered for delimiting the *Open Coastal Water Bodies*. With respect to SPM concentration, *Open Coastal Water Bodies* should be extended to further offshore areas until concentrations do not differ more than one order of magnitude from the values recorded at the reference station at the adjacent category B *Open Coastal Water Body*. This broad interval is designed to discriminate alterations due to estuarine discharges from natural variations occurring in the SPM concentration field.

(iii) Contaminants may behave non-conservatively from transitional to coastal waters, and consequently salinity is insufficient to trace the dispersion of contaminants in the coastal zone. Since contaminants are influenced by the pathways of fine suspended particulate matter and incorporated in biogenic particles, the limits of *Open Coastal Water Bodies* should be defined taking into account the contaminant concentration in both the dissolved and particulate fraction. In this case concentrations should be normalised to aluminium or carbon, according to the affinity of contaminants to particle surfaces, in order to minimise differences related to the particle nature. *Open Coastal Water Bodies* should be extended until contaminant concentrations reach less than 100% of the average values registered in category B *Open Coastal Water Bodies* located nearby. Again, the interval here considered is broad in order to avoid taking into account variations due to the nature of the particles.

The proposed methodology for delimiting category A *Open Coastal Water Bodies* is schematically presented in Figure 4. The outer limit of each *Open Coastal Water Body* is searched sequentially by values of salinity, SPM concentration and contaminant concentration, taking into account reference conditions.

Time scale of observations

Macrotidal and mesotidal shallow ecosystems exchange a large proportion of their water volume with the ocean on a tidal rhythm. Observations carried out near the outlet channel at low tide of spring tides thus better reflect the presence of estuarine-derived material, and generally conditions differ substantially from those near high tide. Since exchanges vary seasonally with the river flow regime the extension of each *Open Coastal Water Body* also increases accordingly. The limit should be calculated (Figure 4) for typical winter river flows and around low spring tide.

Extreme flood conditions should not be considered because they will possibly influence broader areas only on decadal timescale.

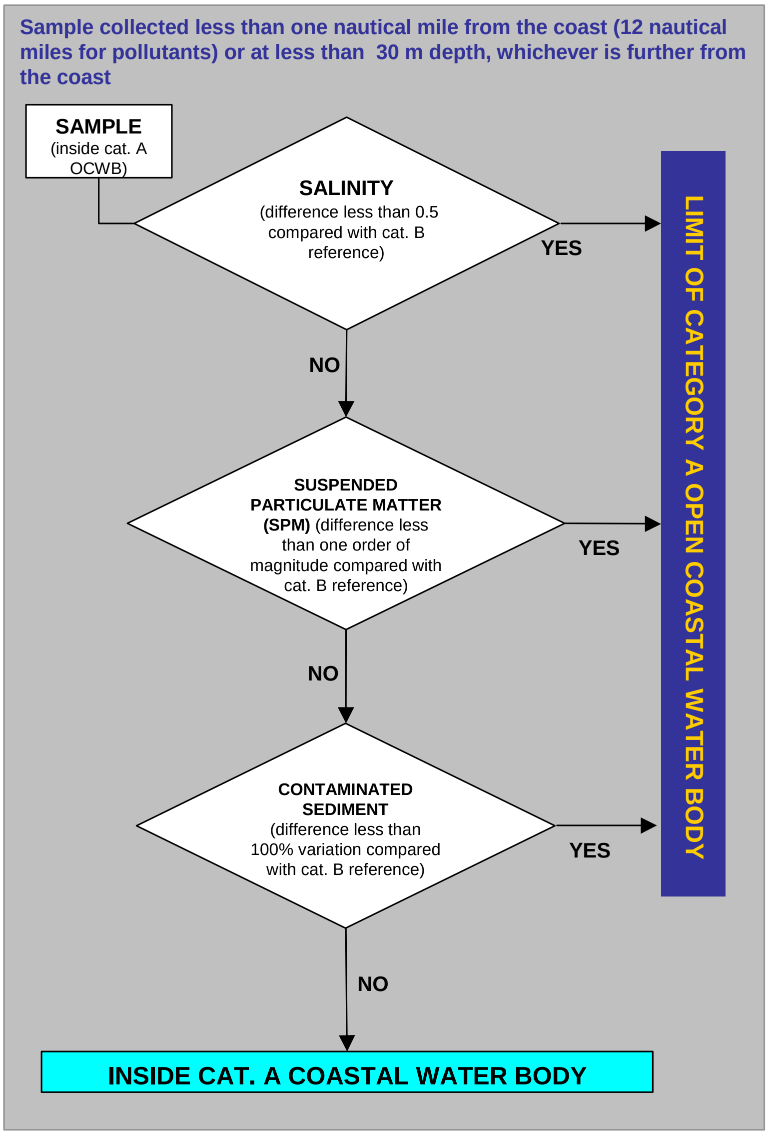


Figure 4 - Schematic representation of the methodology proposed to define open coastal water bodies

Merging coastal zones contiguous to estuaries

The WFD guidance states that “where there are numerous and significant differences in status the number of water bodies should also be numerous, but water bodies will tend to be larger in size and fewer in number”. In certain regions the distance between estuarine outlets may be shorter than the size of *Open Coastal Water Bodies* if the individual influence of each estuarine system is considered. This overlapping effect may result from either strong freshwater discharges or coastal water circulation. In these cases

coastal regions adjacent to contiguous estuarine systems should be merged into a single *Open Coastal Water Body*.

Category B Open Coastal Water Bodies

Open Coastal Water Bodies that are not directly influenced by material derived from land should be defined taking into account the typology of the coast and the existence of morphological features that export material to the coastal waters (size of Category A *Open Coastal Water Bodies*).

Monitoring units

To avoid a large number of *Open Coastal Water Bodies* in zones of small perturbations it may be convenient to consider individual monitoring units within both types of *Open Coastal Water Body*. Examples of possible monitoring units are areas in the proximity of submerged sewage outfalls or areas of coastal upwelling that show rapid increase of nutrients and of consumption by phytoplankton blooms.

Transitional and restricted coastal waters

The methodology for division of transitional and restricted coastal waters into water bodies is illustrated in Figure 5. The approach is applicable to estuaries and to restricted coastal areas such as lagoons or ria systems, and therefore includes transitional waters (*sensu* WFD) and some coastal water types.

Natural characteristics

Morphology and salinity are natural factors that strongly influence the processes controlling the effect of human pressures on the state of water bodies. Morphological characteristics affect hydrodynamics and mixing, and salinity is a controlling parameter for biogeochemical processes. As a result, these factors were considered primary dividers for the delimitation of water bodies. The morphological and salinity factors are combined to identify the set of water bodies that derives from these natural characteristics of the systems.

1. Morphology

An adimensional shape factor (Eq. 1) was used for morphological classification. This parameter reflects the dominance of interface or water column processes. For instance, when the ratio σ_i is high, benthic processes and water-atmosphere exchanges tend to control state.

$$\sigma_i = \log\left(\frac{w_i}{\left|\overline{z}_i\right|}\right) \quad (1)$$

Where:
w_i: Mean width of section i (m);
z_i: Mean depth of section i (m).

The final morphological classification is obtained through (a) sub-division; and (b) analysis and aggregation.

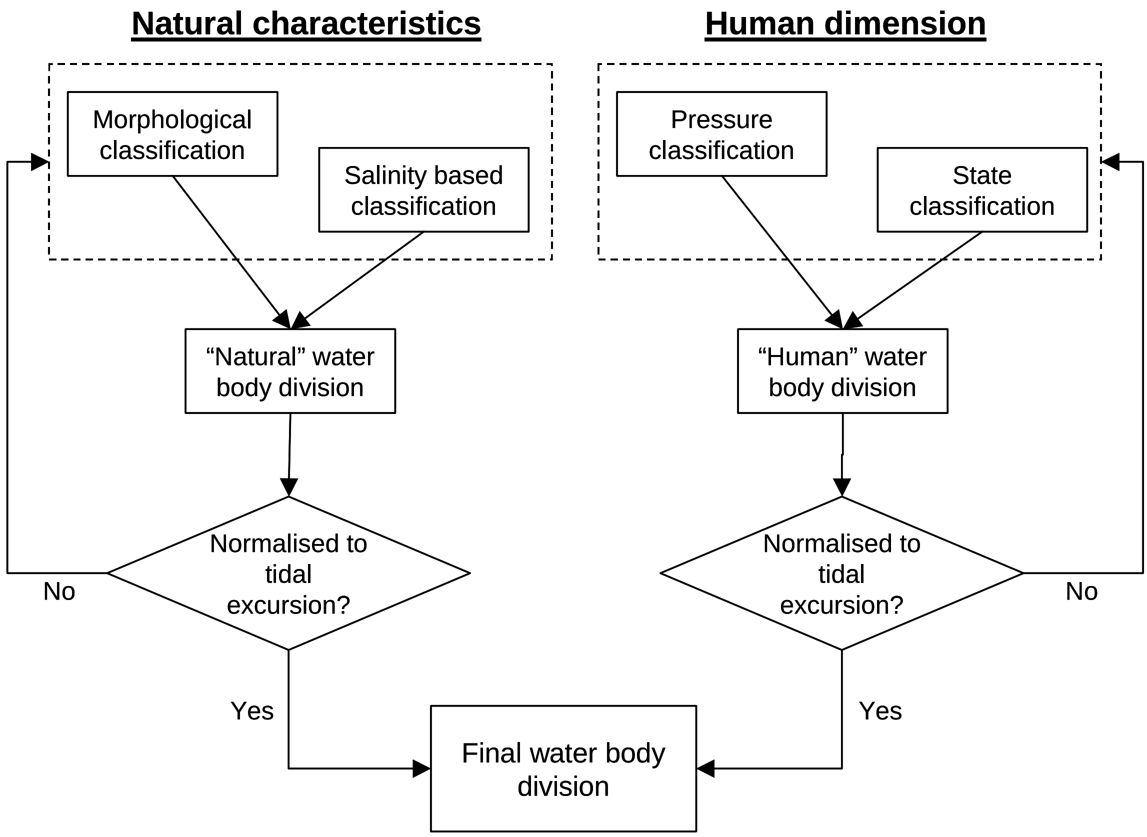


Figure 5 - Stepwise definition of water bodies in transitional and restricted coastal waters

Sub-division

Cross-sectional profiles are drawn from bathymetric data using a geographical information system (GIS). The choice of the distance between sections is established as a function of the shape of the system – for a tubular estuary these are equidistant, but for systems with a more complex topography they may be heuristically determined (Figure 6).

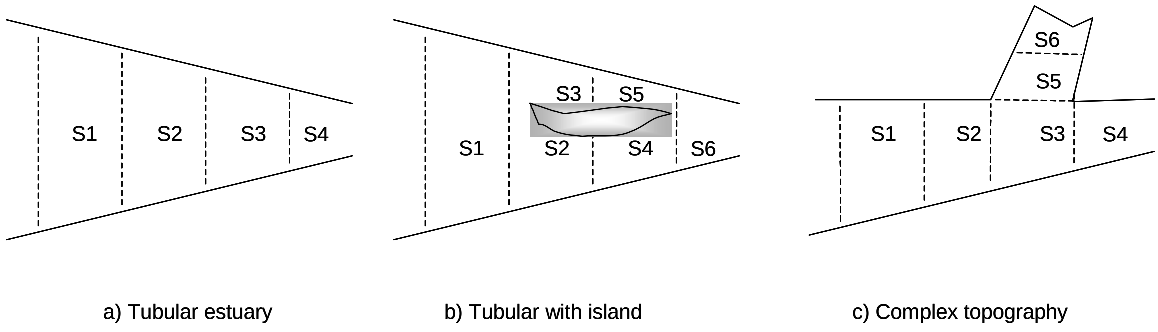


Figure 6 - Plan view of longitudinal division into sections for different estuaries

The cross-sectional profiles are analysed in order to identify sub-units (Figure 7): these would normally be considered separate when two (or more) deeper channels with an intertidal or island area between them occur (Figure 6b and Figure 7c).

Analysis and aggregation

The mean width w_i and mean depth z_i are determined by GIS for each section of the estuary. In areas where the system is split laterally into two or more sections (e.g. Figure 7c), these are considered separately.

The shape factor σ_i is calculated for each section, and compared pair-wise to determine an aggregation index ϕ (Eq. 2). Sections are aggregated longitudinally into water bodies when ϕ is below a threshold value. This critical value was defined heuristically to be 30%.

$$\phi_{i,i+1} = \frac{\left|\Delta\sigma_{i,i+1}\right|}{\left(\sigma_i + \sigma_{i+1}\right)/2} \quad (2)$$

Where:

$\phi_{i,I+1}$: Aggregation factor (no units);

$\Delta\sigma$: Absolute difference between σ_i and σ_{i+1}(no units).

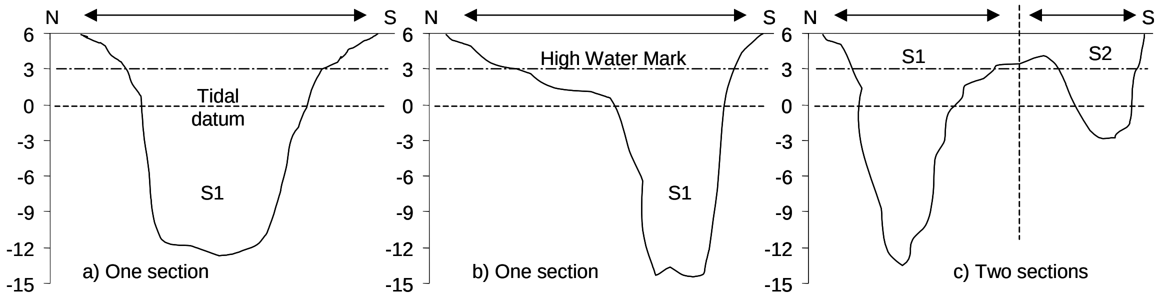


Figure 7 - Lateral division based on morphology, using transverse sections in a hypothetical estuary

2. Salinity

A spatial framework based on salinity zonation was applied to provide an additional natural sub-division of water bodies within an estuary, complementing the morphological division. Three salinity classes were defined, based on the NOAA National Estuarine Inventory; tidal fresh (0-0.5 psu), mixing (0.5 – 25 psu) and seawater (>25 psu) zones, which broadly correspond to the Venice classification. However, the threshold between the seawater and mixing classes (Venice system euhaline/mixohaline) was adjusted to reflect changes in species distribution of floral and faunal communities along the salinity gradient.

Salinity for each station was determined from long-term salinity records and represents annual average, water column average values. The salinity zones are obtained using GIS: tubular (Type 1) estuaries will normally be split into three zones and Type 2 estuaries with a more complex topography and circulation may additionally be divided laterally. Although not all systems have all three zones, this allows a consistent approach for comparisons among highly diverse systems.

3. Harmonisation of the *natural characteristics* division

The results obtained through the application of morphology and salinity dividers are combined into a pre-final set of “natural” water bodies. In cases where the limits derived from morphology and salinity are close together, the pairs are considered as “bands”, and a centreline is defined as a water body separator. In other cases, the combination of the two factors will potentially lead to more water bodies.

However, the tidal excursion is first used as a normalization test: if the length of a water body defined through morphology, salinity, or a combination of the two factors is less than the tidal excursion, its size is increased appropriately, which may lead to a decrease in the number of water bodies. The rationale for this test, which is also applied in the *Human dimension* division, is to ensure that small areas are not considered as water bodies, since tidal circulation will cause the same water mass to be in two or more different water bodies. Given that a water body is defined in the WFD as a management unit, where control measures on the significant pressures potentially result in a change in state, excessively small water bodies will be scientifically meaningless.

Human dimension

A guidance document on the application of the WFD to transitional and coastal waters (Vincent et al., 2003) provides the following orientation: “*The need to keep separate two or more contiguous water bodies of the same type depends upon the pressures and resulting impacts. (…) Such an area of one type could therefore be divided into two separate water bodies with different classifications. If there were no impact from the discharge it would not be necessary to divide the area into two water bodies as it would have the same classification and should be managed as one entity.*”

Both aspects are considered herein for water body division from an anthropogenic standpoint. The pressure factor provides an assessment of loading of the relevant substances to an estuary, and the state assessment allows a division in terms of impact of such discharges, based on a sub-set of appropriate metrics. These metrics

are chosen from the list of WFD *Biological Quality Elements* (BQE) and *Supporting Quality Elements* (SQE).

1. Pressure

Determination of pressure on an estuarine system for the purpose of defining water bodies involves the following steps:

- Selection of the significant pressure, and choice of representative variables;
- Assessment and partitioning of loads;
- Normalisation, analysis and aggregation.

<u>Selection of the significant pressure and representative variables</u>

A variety of pressures may be considered in the application of the WFD for the purpose of defining water bodies, with the constraint that the most significant pressure should be selected. In the examples given here we have chosen nutrient loading, with eutrophication symptoms (*sensu* Bricker et al., 2003) in the water bodies as a potential impact on state.

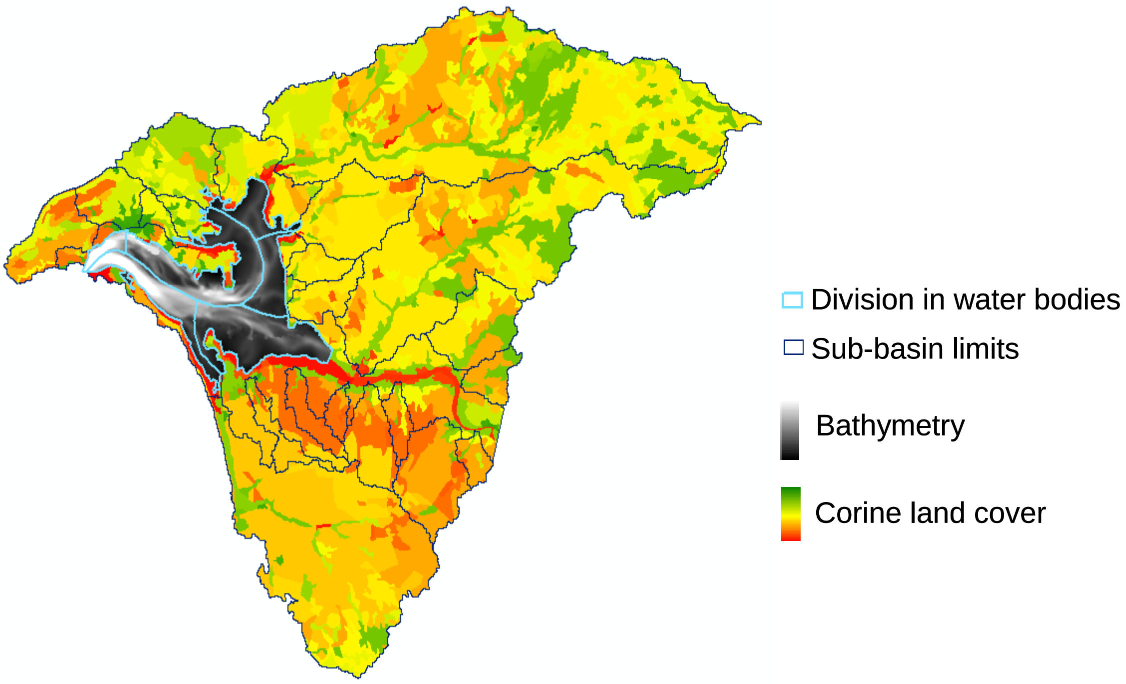


Figure 8 - Pressure aggregation based on Corine land cover mapping

Assessment and partitioning of loads

This may be done through a combination of different techniques, such as source inventories or modelling (Smith et al., 1997; Valiela et al., 1997; Kuo et al., 1999; Alexander et al, 2001; Lee et al., 2001; Alexander et al., 2002; Valiela et al., 2004). For our work the CORINE land cover database was used (Figure 8), and land use coefficients were applied to determine nitrogen and phosphorus loads. In order to partition the load discharging to different parts of an estuary, the watershed was divided into sub-basins using a digital terrain model (Figure 8), and the final N and P loading was then determined for each section of the watershed.

Normalisation, analysis and aggregation

In order to determine the "pressure-defined" zones of an estuary, the following approach was used: (a) the N and P loading for each watershed sub-basin was normalised by dividing by the estuary shoreline length of the sub-basin; (b) the limiting nutrient for primary production was calculated from the Redfield ratio; and (c) a similarity index τ was defined heuristically, and used to aggregate contiguous lengths of the shoreline with similar pressure.

$$\tau_{i,i+1} = \frac{\left|\Delta\lambda_{i,i+1}\right|}{(\lambda_i + \lambda_{i+1})/2} \quad (3)$$

Where:

$\tau_{i,I+1}$: Aggregation factor (no units);
λ_i: N load normalised per length of shoreline (kg N y^{-1} m^{-1});
$\Delta\lambda$: Absolute difference between λ_i and λ_{i+1}(kg N y^{-1} m^{-1}).

This index was calculated using Eq. 3, and is analogous to the approach used in the morphology component. Contiguous sub-basins with a value of τ < 30% were aggregated pair-wise, providing a pressure-derived definition of water bodies.

2. State

The use of appropriate metrics of state to contribute to water body definition is justified because the relationship between pressure and state is strongly influenced by estuarine geomorphology, hydrodynamics and ecological structure. For instance, estuaries subject to similar nutrient-related pressure often exhibit totally different eutrophication symptoms, and in some cases, no symptoms at all. Factors such as water residence time (e.g. Ketchum, 1954; Lucas et al., 1999; Tett et al., 2003), tidal range (Alvera-Azcarate et al., 2003), turbidity (May et al., 2003) and grazing (e.g. Cloern, 1982) play a major role in determining the nature and magnitude of symptom expression.

The approach followed in the present methodology consists of two steps:

- Selection of a sub-set of appropriate parameters;
- Data analysis and aggregation.

<u>Parameter selection</u>

Appropriate parameters are chosen from the list of BQE and SQE. The relevance is determined from:

(a) Significant pressures - for instance, if these result in N and P discharge, water column chlorophyll *a* (chl *a*) might be considered appropriate, whereas if the main issue is xenobiotic emissions, lead or mercury in sediments might be the elements of choice;

(b) Key characteristics of the estuarine system – for instance, if eutrophication symptoms are the general category under consideration, opportunistic benthic macroalgae might be more appropriate than chl *a* for fast-flushing or strongly light-limited estuaries.

<u>Data analysis and aggregation</u>

Data on the relevant variables collected for an estuary (e.g. from field measurements or remote sensing) are assimilated at an appropriate time scale and plotted as GIS surfaces. Aggregation may be carried out by establishing concentration dividers for each variable, and using the overlapped surfaces to define the state component of water bodies. This may be done on the basis of established classification systems

(e.g. MacDonald et al., 1996), or where these do not exist, using a heuristic approach.

In the present study, chl *a* and dissolved oxygen (D.O.) were used as eutrophication symptoms, with data assimilated over a period of one year. Classification thresholds follow Bricker et al. (1999), using 90th and 10th percentile cut-off points for chl *a* and D.O. respectively (Bricker et al., 2003).

3. Harmonisation of the *human dimension* division

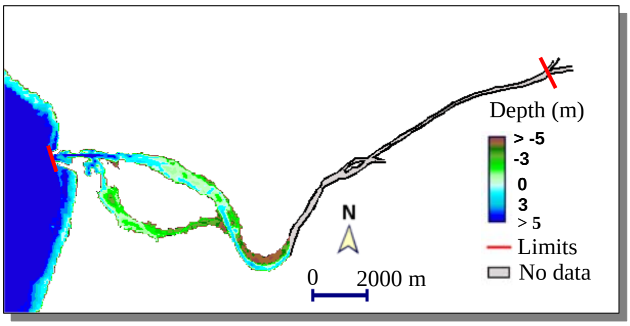
As for the “natural” division, pressure and state results are combined into a pre-final set of water bodies reflecting the *human dimension*. The water bodies defined through the analysis of state are used essentially in two ways: (a) to link opposite shorelines where there is no significant gradient in state; and (b) to join or divide contiguous sections based on pressures when there is no significant change in impact, following Vincent et al (2003). As indicated previously, tidal excursion is also used as a normalization test.

Final definition of water bodies

The final definition of water bodies for an estuary is obtained by combining and harmonising the natural and human components. Boundaries that are close together are aggregated as described previously, by considering a boundary “band” which is then reduced to a centreline. If required, the tidal excursion is used as a “common sense” test to define a final set of water bodies.

EXAMPLES OF APPLICATION TO WELL STUDIED SYSTEMS

In order to test the methodology proposed for transitional and restricted coastal waters, a detailed analysis was carried out for the Mondego and Sado estuaries (Figure 9). The key characteristics of these systems are given in Figure 10.



The Mondego estuary is a long, tubular estuary which is divided into two channels in the lower reaches, whereas the Sado estuary is broad in the upper reaches, exhibits a much more complex topography, and is connected to the ocean through a narrow deep channel. It exhibits a two-dimensional circulation, significant intertidal areas, and has a range of distinct and sometimes conflicting uses; these include fishing, aquaculture, recreation and tourism, but also port activities and effluent disposal.

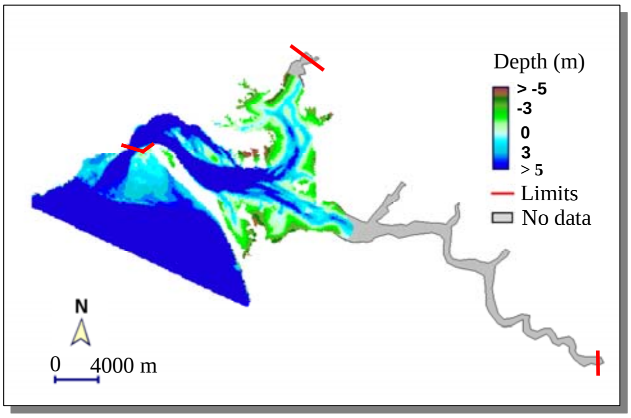


Figure 9 - Map of the two systems used as case studies

Figure 10 – Key features of the Mondego estuary and Sado estuary (Ferreira et al, 2003)

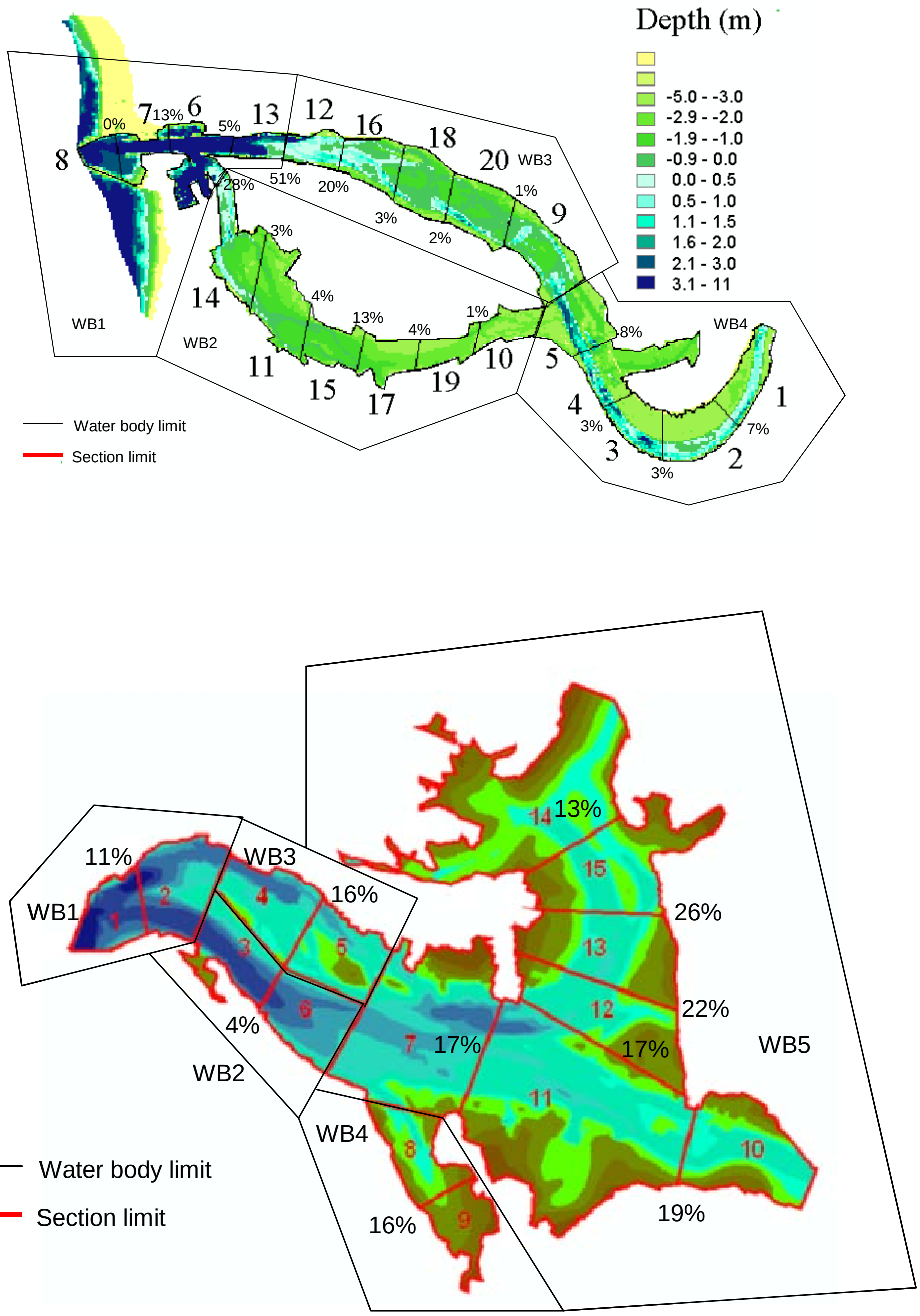
	Mondego estuary	Sado estuary
Volume (10^6 m^3)	22	500
Surface area (km^2)	6.4	180
River flow (m^3s^{-1})	80	40
Tidal range (m^3)	3.0	2.7
Population	66,000	128,000
Mean water residence time (d)	North channel: 2 South channel: 9	32

The next figures (Figures 10-14) show the detailed analysis carried out for the two estuaries in order to test the methodology for division.

Natural characteristics

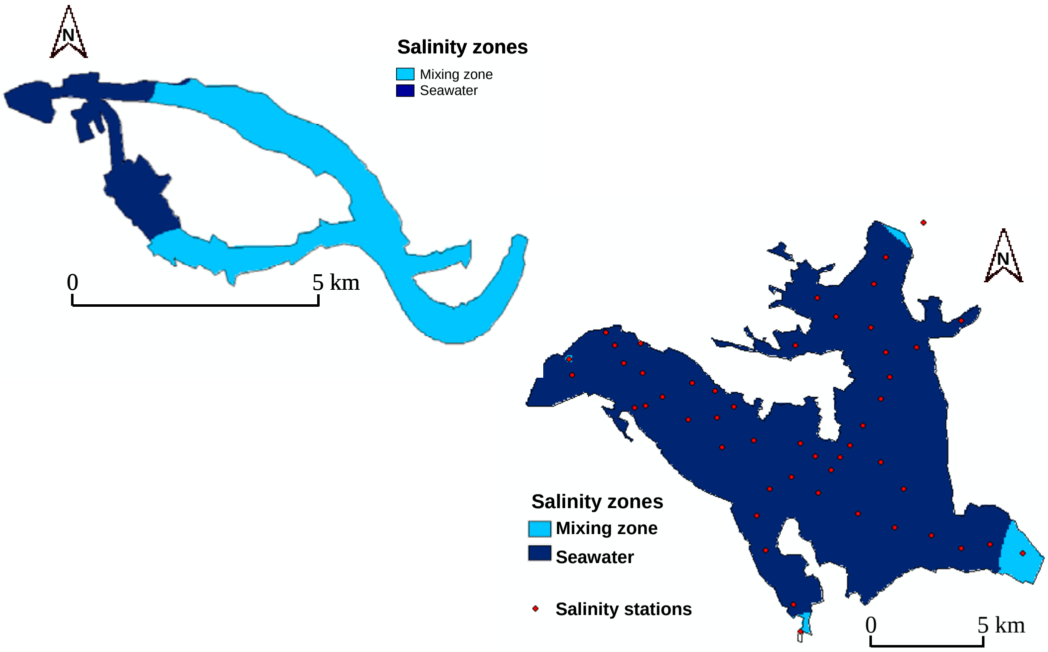
The morphological analysis (Figure 11) analysis the similarity between contiguous section using the ϕ criterion, and identifies four water bodies in the Mondego and five in the Sado.

Figure 11 - Longitudinal division of the Mondego and Sado estuaries as an example for morphological analysis, showing GIS sections, ϕ values and definition of water bodies based on morphology



The Sado WB5 aggregates two channels of distinct characteristics, the Alcácer and Marateca channels, into a single water body.

Figure 12 - Division of the Mondego (left) and Sado (right) estuaries based on salinity classes



The salinity surfaces shown in Figure 12 were based on measured data obtained over a number of years, and are median values at each sampling station, covering all seasons and tidal situations. These surfaces do not divide the estuaries into more water bodies. In the case of the Mondego, WB2, WB3 and WB4 become a single water body, but the divider between the south channel and the mouth is now further upstream. In the case of the Sado, the salinity distribution in the estuary is typical of a coastal lagoon, with almost the whole of the system having salinities greater than 25 psu.

Human dimension

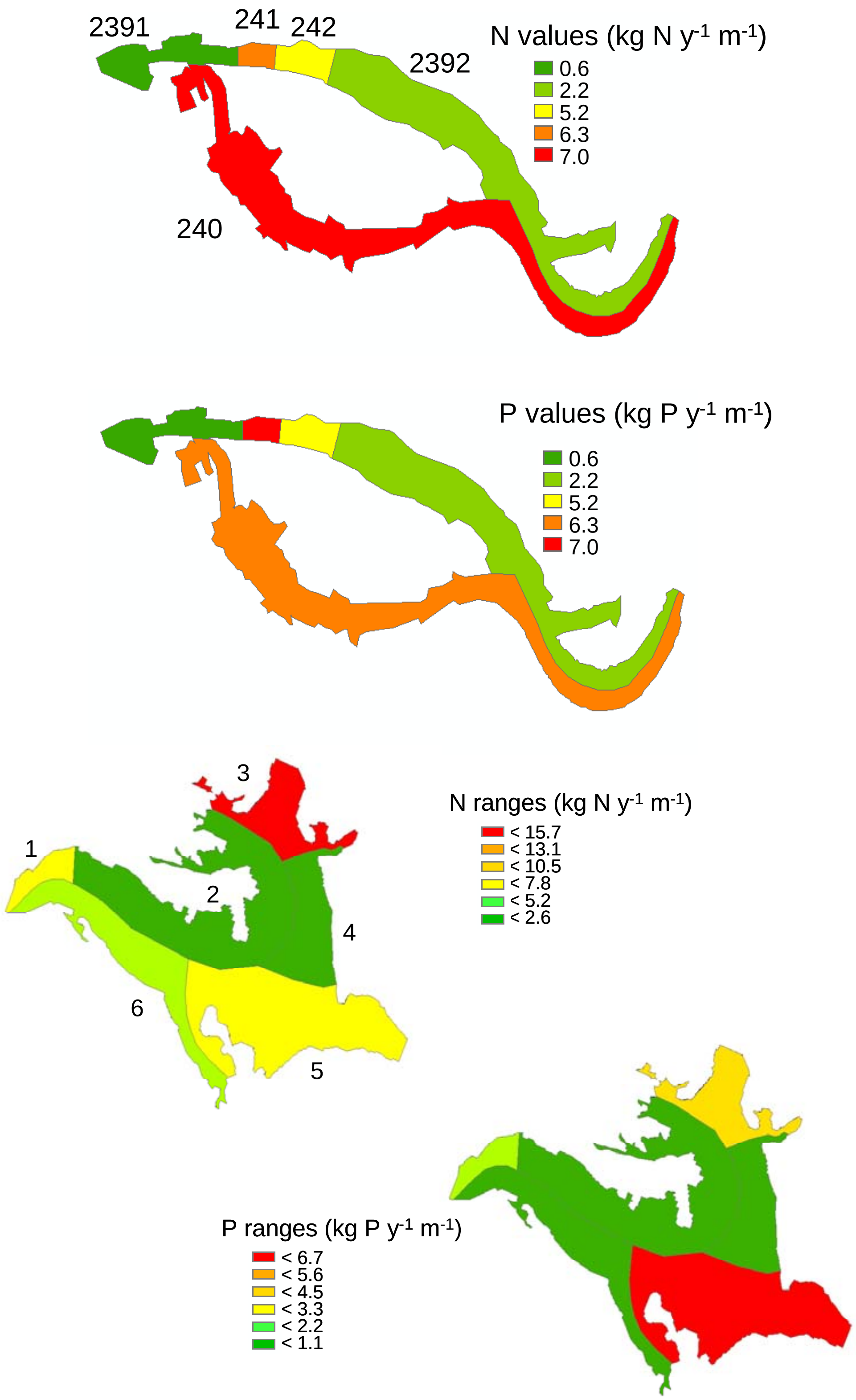
The anthropogenic criteria for division of the two systems into water bodies were determined in two stages.

<u>Pressure</u>

The assessment of pressure was carried out by means of a land cover analysis from CORINE maps, normalised to the discharge perimeter of each watershed sub-basin.

In this analysis, nutrient discharge was considered to be the most significant pressure, and therefore N and P loading was evaluated.

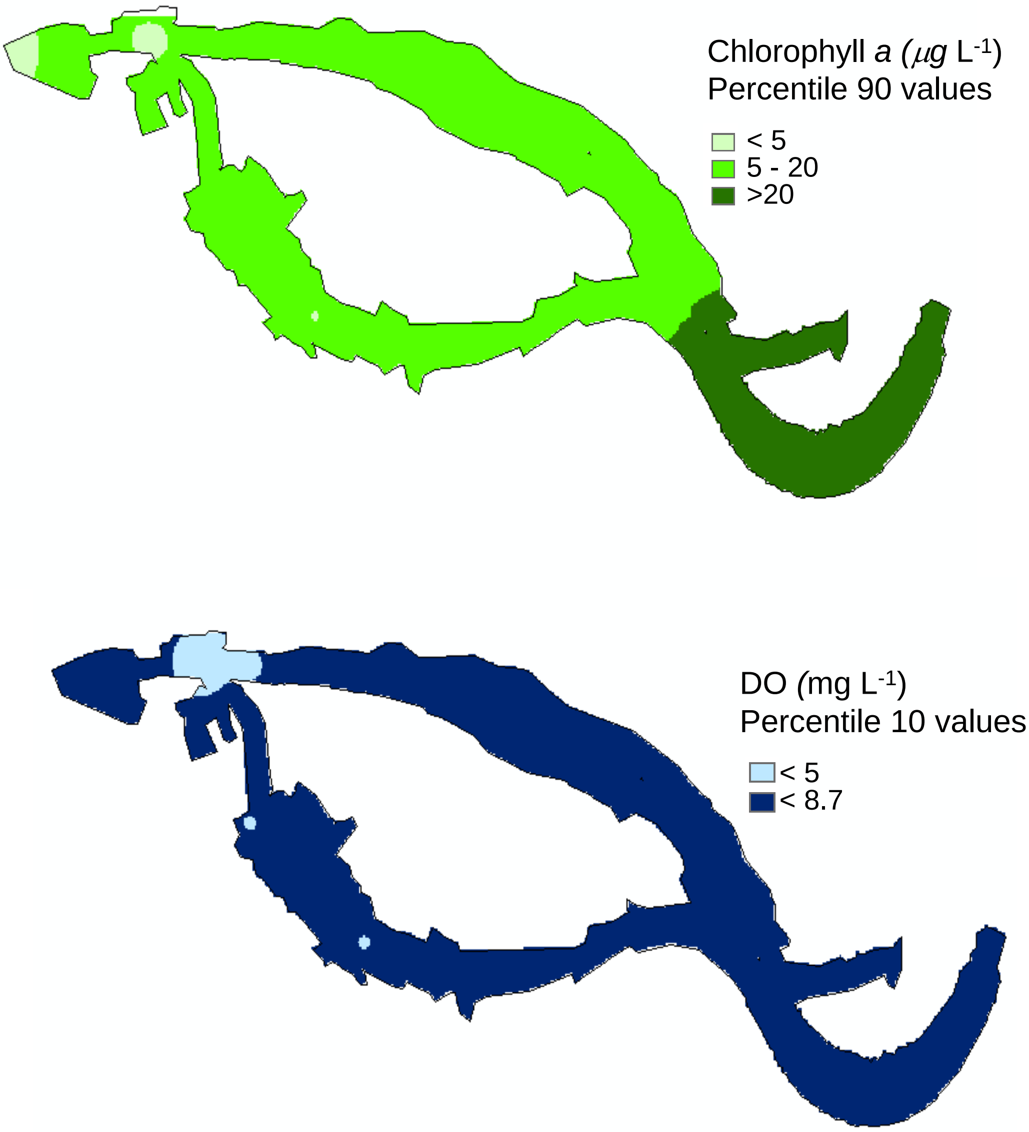
Figure 13 - Division of the Mondego and Sado estuaries based on watershed nutrient pressure



The choice between N and P as the key element for pressure was carried out by calculating the Redfield ratio of the discharges.

In both cases the N/P discharge ratio (in mass) was between 3-4, suggesting the use of N as the element for analysis. Figure 13 shows the application of the pressure metric.

Figure 14 - Division of the Mondego estuary based on state



For the Mondego, the τ threshold (Eq. 3) distinguishes between sub-basins 2391 and 241, 242 and 2392, and 2391 and 240, with a value of τ of about 160%. This would lead to the definition of four water bodies. In the case of the Sado, all the contiguous

sub-basin values have values of $\tau > 30\%$, suggesting the definition of six separate water bodies.

<u>State</u>

State was determined through the selection of appropriate BQE and SQE, which were selected based (a) on the significant pressure; and (b) on the natural characteristics of the two systems. Since nutrient input was chosen as the relevant pressure, state was evaluated using BQE and SQE selected from a range of primary and secondary symptoms of eutrophication (Bricker et al., 2003).

Figure 14 shows the GIS surfaces for the Mondego estuary for chl *a* and D.O. The limits shown are for the percentile 90 and percentile 10 respectively, as indicators of typically elevated (for chl *a*) and low (D.O.) values, following Bricker (2003) and Ferreira et al. (2003).

The distribution of these variables in the Mondego suggest two water bodies, using the primary eutrophication symptom chl *a*, and one water body, using the secondary symptom D.O. The southern channel has well-known issues of opportunistic macroalgal blooms, but estuary-wide data were not available for a comparative overview.

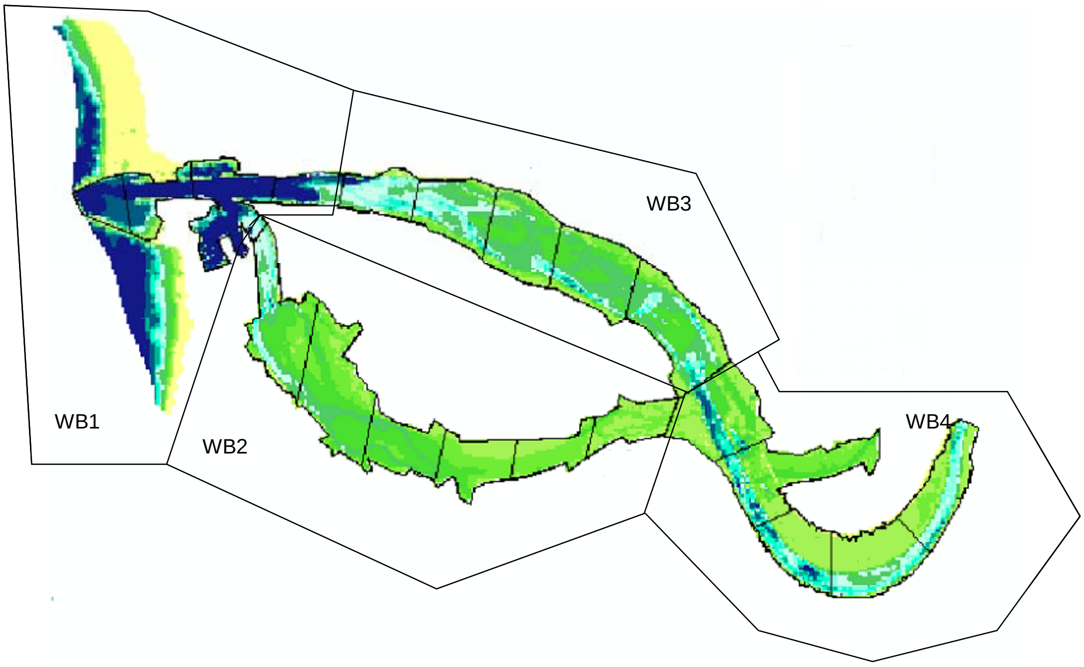
The Sado (not shown) was assessed by means of the same BQE and SQE, which showed no detectable differences throughout the estuary, both for chl *a* and D.O.

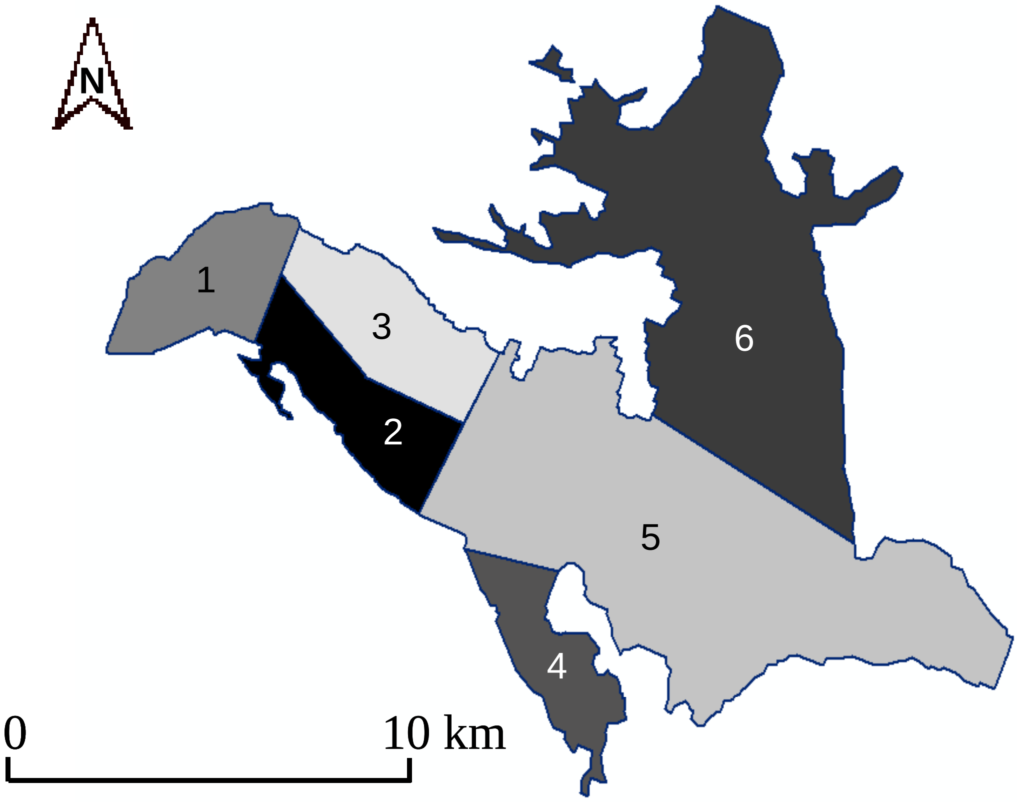
Synthesis of natural and human characteristics

Expert knowledge suggests that the southern channel of the Mondego should be separated from the remainder of the estuary as a distinct water body, due to lower depth, reduced circulation and higher residence time (indicated by morphology and salinity criteria in this methodology).

For the Mondego estuary, a combination of the various criteria, taking into account tidal excursion, would suggest the division shown in Figure 15. Expert knowledge would further reduce the four water bodies shown to three (see Results section).

Figure 15 - Final water bodies for the Mondego and Sado estuaries





For the Sado, taking into account the differentiation due to morphology and pressure, but considering that salinity and the state indicators do not vary over the whole system, six water bodies are proposed, which roughly correspond to the

morphological and pressure dividers. The two upstream channels are separated by the different pressure patterns.

RESULTS

This section presents the set of water bodies proposed by the MONAE project team for Portuguese transitional and coastal waters. The *Open Coastal Water Bodies* are shown first, with a description of the decision-making process.

The *Transitional and Restricted Coastal Water Bodies* are shown in the final section, based on the application of the methodology detailed previously. The diagrams shown are based on the application of the natural and human criteria, based on quantitative analysis, semi-quantitative analysis or heuristics, depending on the data available for each system.

Open Coastal Waters

On the basis of the methodology described above for the definition of *Open Coastal Water Bodies*, morphological features and conditions of the Portuguese coast, and coastal water typologies defined previously (Bettencourt et al, 2003) the following *Open Coastal Water Bodies* are proposed (Figure 16):

(i) Category A

(a) CWB-I-1, between Minho and Douro adjacent coastal areas. Several authors show that the fields of salinity and suspended particulate matter (SPM) concentration successfully trace the dynamics of this region. The Douro plume is dominant until the Minho in spite of the other small discharges to the coast. In addition, concentrations of metals, PCBs and DDT are in general higher in this area than in the south (Caetano & Vale, 2003; Quental et al, 2003). The differences are more pronounced during periods of higher river flows. Consequently, homogeneity may be assumed in the area between Douro and Minho and for monitoring purposes considered as a single coastal water body. A general monitoring plan can be carried out by regularly distributing the observation stations all over the area but placing more emphasis on the mouths of the estuaries with special influence in the coast (Douro, Minho and Lima in decreasing order of importance).

(b) CWB-I-2, adjacent to the Ria de Aveiro. The Ria de Aveiro exchanges dissolved and particulate material to the adjacent coastal zone, particularly during winter when the lagoon receives large quantities of freshwater.

(c) CWB-I-3 - adjacent to Mondego estuary. Several authors have showed the eutrophication of the southern channel of the Mondego estuary (Pardal et al, 2001), the dynamics of primary producers (Lillebo et al, 1999) and interactions with N and P (Lillebo et al, 2002; Lillebo et al, 2004). Sediment chemical composition suggests low contamination in the north channel and export of material to the sea during periods of high flow (Vale et al, 2001; Pereira et al, in press).

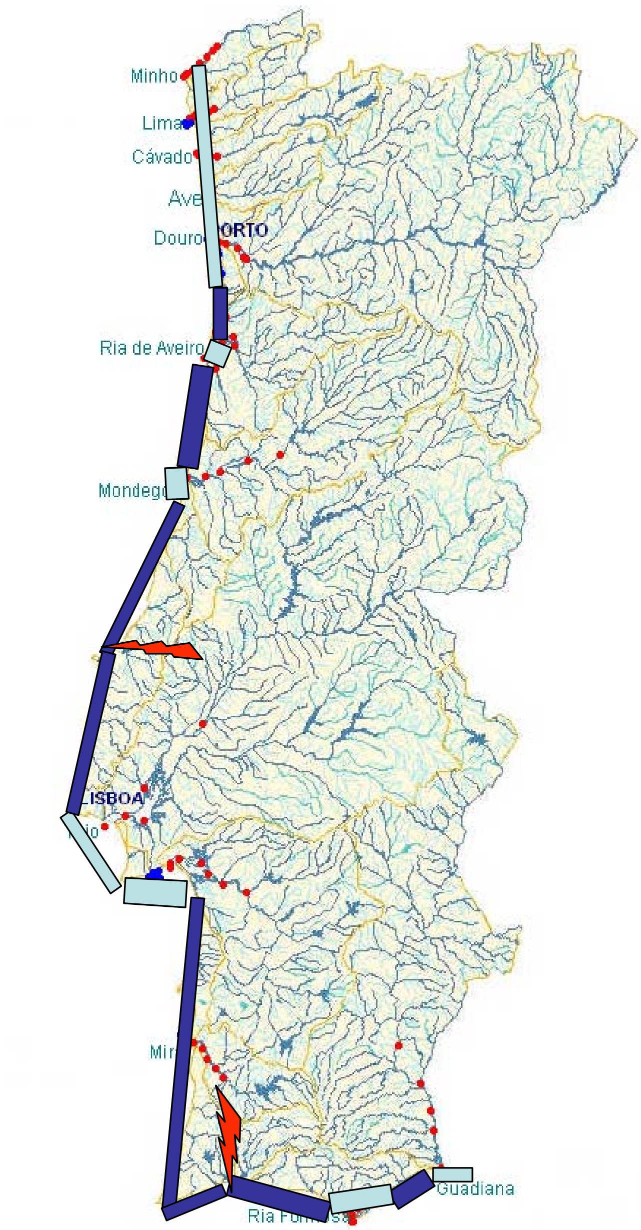


Figure 16 - Proposed Coastal Water Bodies for the Portuguese coast

Material exported includes nutrients derived from the diffuse sources in the drainage basin and from domestic sewage (Lopes, 2003) and potentially contaminants incorporated in the sediments (Monterroso et al, 2002; Pereira et al, 1998) that may be resuspended in the water column (Pereira et al, 1998) and eventually dispersed in association with plankton (Monterroso et al, 2003).

(d) CWB-I-4 – adjacent to the Tagus estuary. Many works showed the importance of the Tagus estuary in the adjacent coastal area in terms of modelling (Fortunato et al, 1997; Cancino & Neves, 1999; Oliveira et al, 2000) suspended sediments (Vale & Sundby, 1987; Joanneau et al, 1998), contaminants (Vale, 1986; Vale, 1990; Caetano & Vale, 2003; Quental et 2003), nutrients (Cabeçadas & Brogueira, 1997),

plankton (Moita, 2001), nursery for commercial fisheries (Costa & Bruxelas, 1989; Cabral & Costa, 1999).

(e) CWB-I-5 – adjacent to Sado estuary. The inner bay of the Sado estuary receives inputs from industrial activities, domestic sewage and diffuse sources in the drainage basin. Analysis of sediments (Cortesão & Vale, 1995; Gil & Vale, 2001; Gil & Vale, 1999) fish and oysters (Ferreira & Vale, 2001; Vale et al, 1998) suggest confined areas of contamination. In periods of high flow the export of contaminants was shown (Joanneau et, 1998; Vale et al, 1993). The interactions between the environmental variables and benthic communities were assessed (Costa, 1988; Rodrigues, 1992; Correia & Costa, 2000).

(f) CWB-I-6 – adjacent to Ria Formosa. Although freshwater inputs to Ria Formosa are negligible during most of the year (Ventura-Soares, 2001) substantial amounts of anthropogenic material derived from domestic sewage enter directly into the lagoon, causing eutrophication in confined areas (Newton et al, 2003). Because the lagoon is shallow and strongly influenced by the tidal excursion, around 75% of the water volume is renewed at spring tides. Recent work has showed the seasonal variation of exchange of nutrients with the adjacent coastal areas (Falcão & Vale, 2003).

(g) CWB-I-7 – adjacent to the Guadiana estuary. The Guadiana estuary has been considered extremely sensitive to heavy rain and runoff. During these episodes the estuarine area is filled with freshwater and measurements show the export of substantial quantities of dissolved and particulate matter to the adjoining coastal area (Jorge da Silva, 2003). Although the drainage basin is mainly a rural area organic pollutants from diffuse sources may be exported (Ferreira et al, 2003) and metals from soil erosion and domestic sewage near the mouth.

(ii) Category B

(a) CWB-II-1- between Douro (CWB-I-1) and Aveiro (CWB-I-2), where no direct influence of significant freshwater input was recorded.

(b) CWB-II-2 – between Aveiro (CWB-I-2) and Mondego (CWB-I-3) where no direct influence of significant freshwater input was recorded.

(c) CWB-II-3 – between Mondego (CWB-I-3) and the Cape Carvoeiro, corresponding to a wave exposed area as defined previously (Bettencourt et al, 2004) and including the Nazaré canyon.

(d) CWB-II-4 – between the Cape Carvoeiro and Cape of Roca, a moderately wave exposed area.

(e) CWB-II-5 – between Sado (CWB-I-5) and Ponta da Piedade, including the southwest coastal area of Portugal where most of freshwater systems do not reach

the coast and several land-locked coastal lagoons are formed. The criteria to extend this *Open Coastal Water Body* to Ponta da Piedade in the south coast is based on similarities of meteorological and wave conditions.

(f) CWB-II-6 – between Ponta da Piedade and Ria Formosa (CWB-I-6), where no direct influence of significant freshwater input was recorded.

(g) CWB–II-7 – between Ria Formosa and Guadiana (CWB-I-7), where no direct influence of significant freshwater input was recorded.

Transitional and Restricted Coastal Waters

On the basis of the approach described, the following figures itemise the water bodies for all the transitional and coastal systems (types A1 to A4) listed in Figure 3.

Figure 17 - Water bodies for the Minho estuary

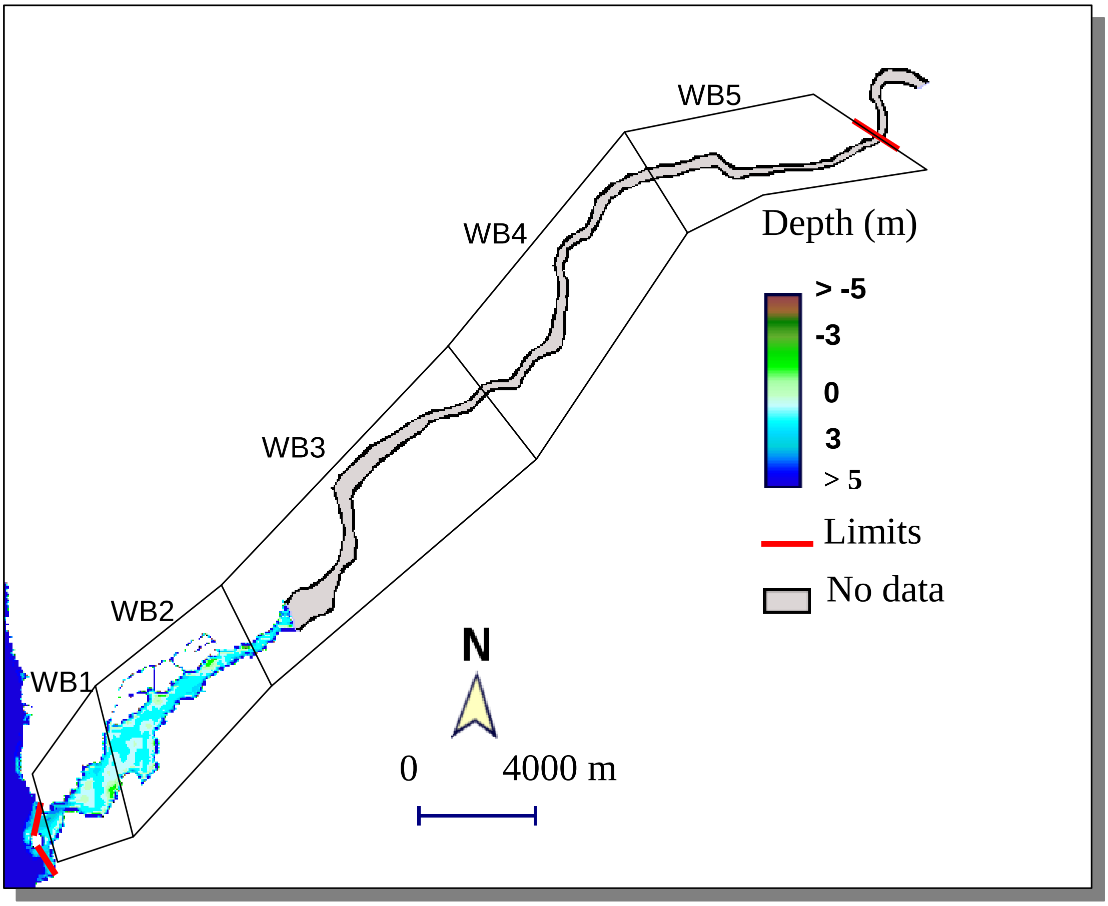


Figure 18 - Water bodies for the Lima estuary

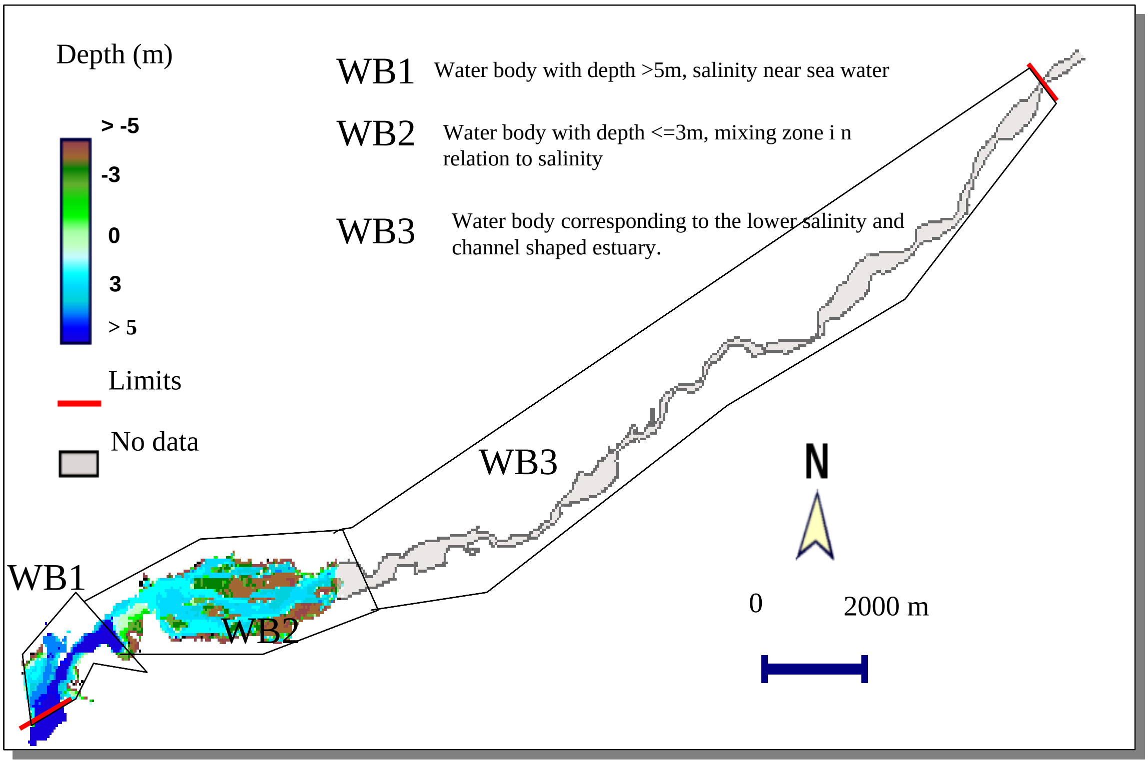


Figure 19 - Water bodies for the Douro estuary

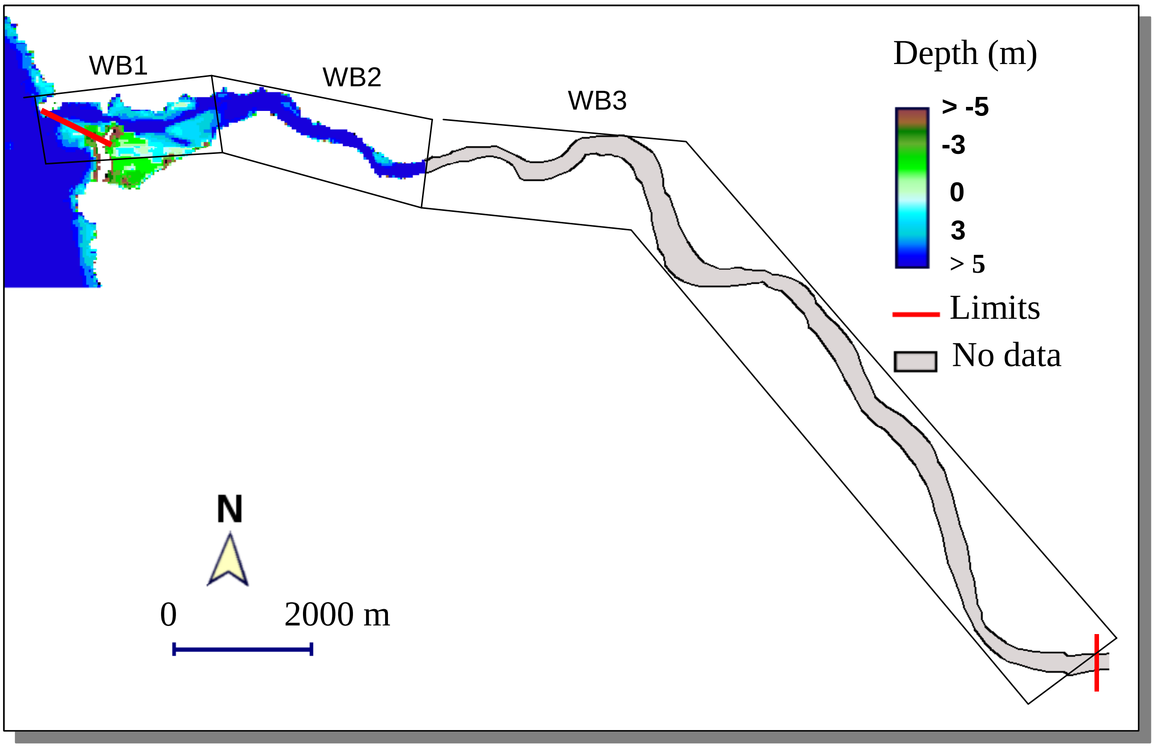


Figure 20 - Water bodies for the Ria de Aveiro

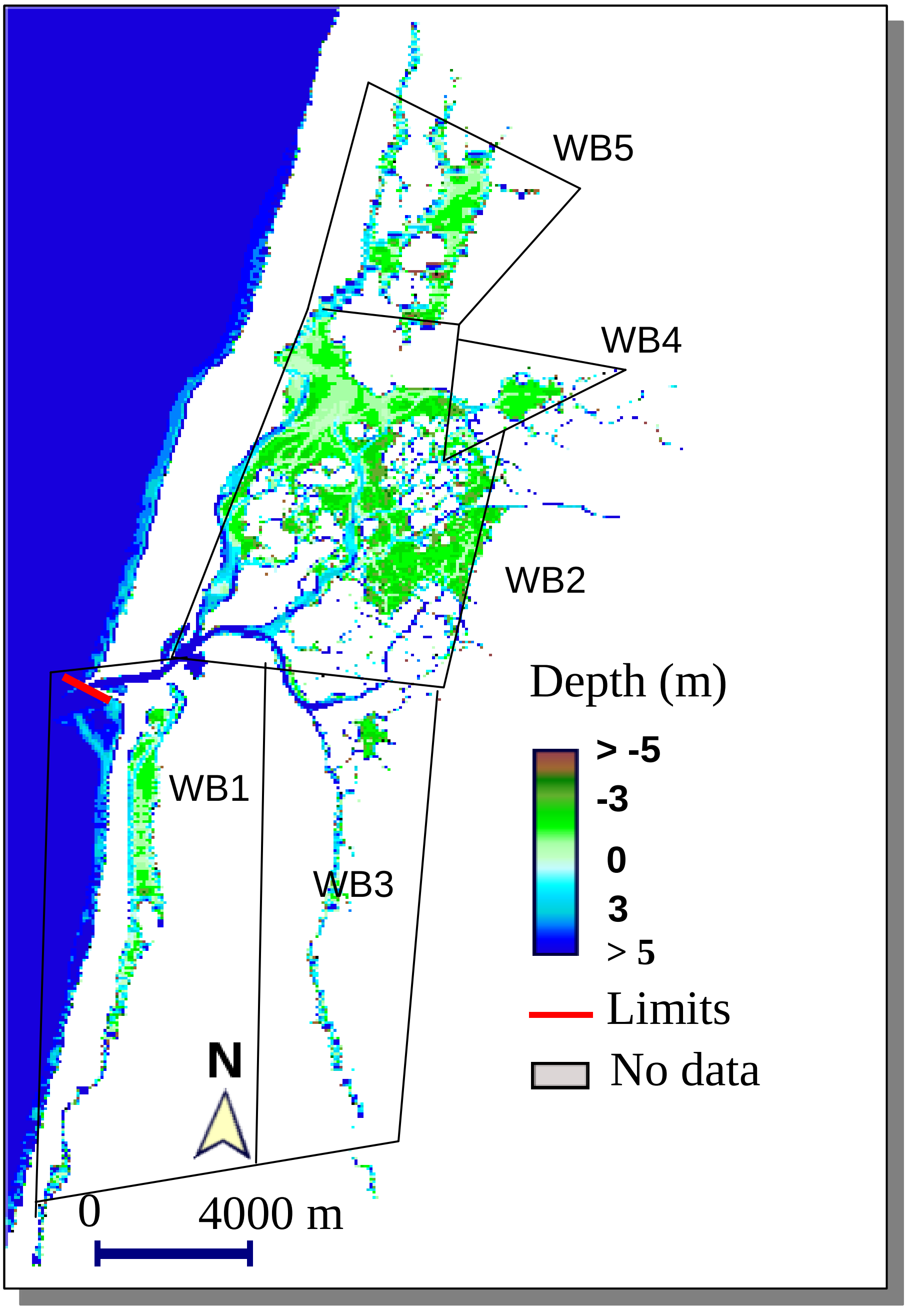


Figure 21 - Water bodies for Lagoa de Óbidos

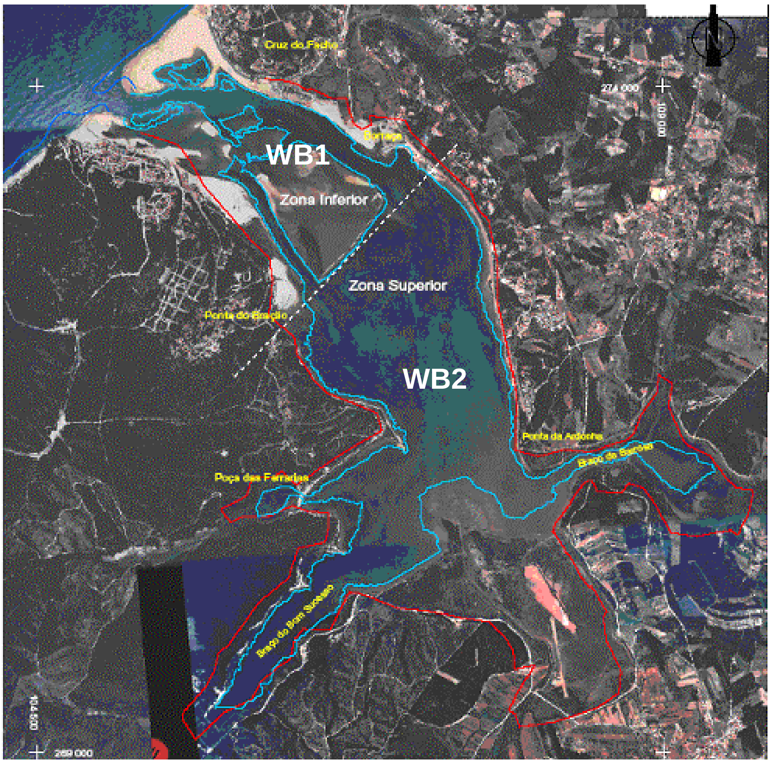


Figure 22 - Water bodies for the Mondego estuary

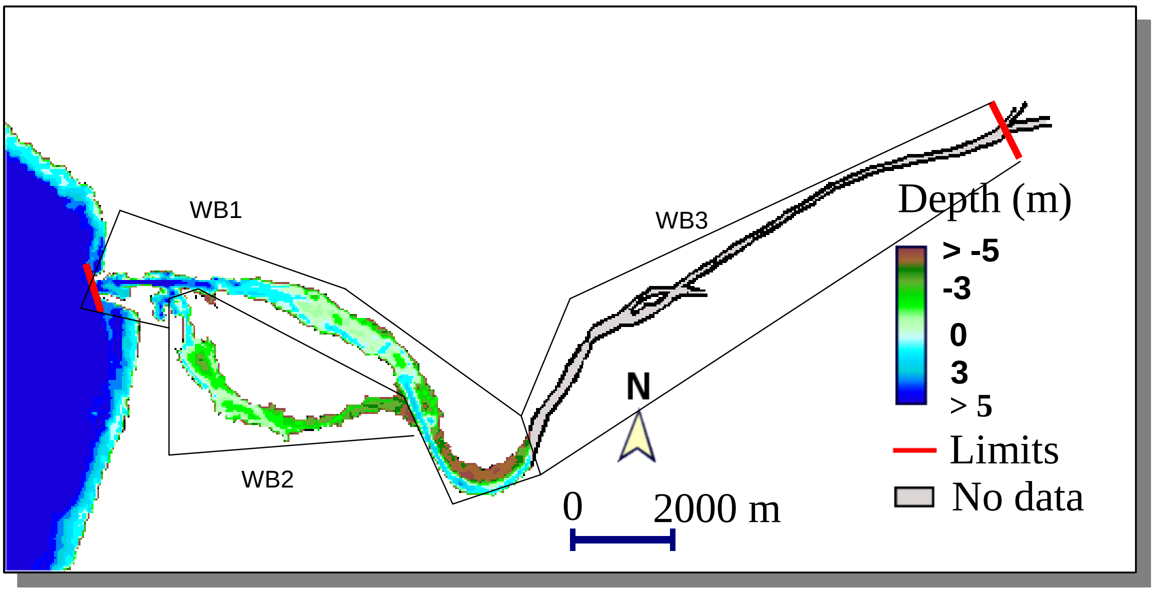


Figure 23 - Water bodies for the Tagus estuary

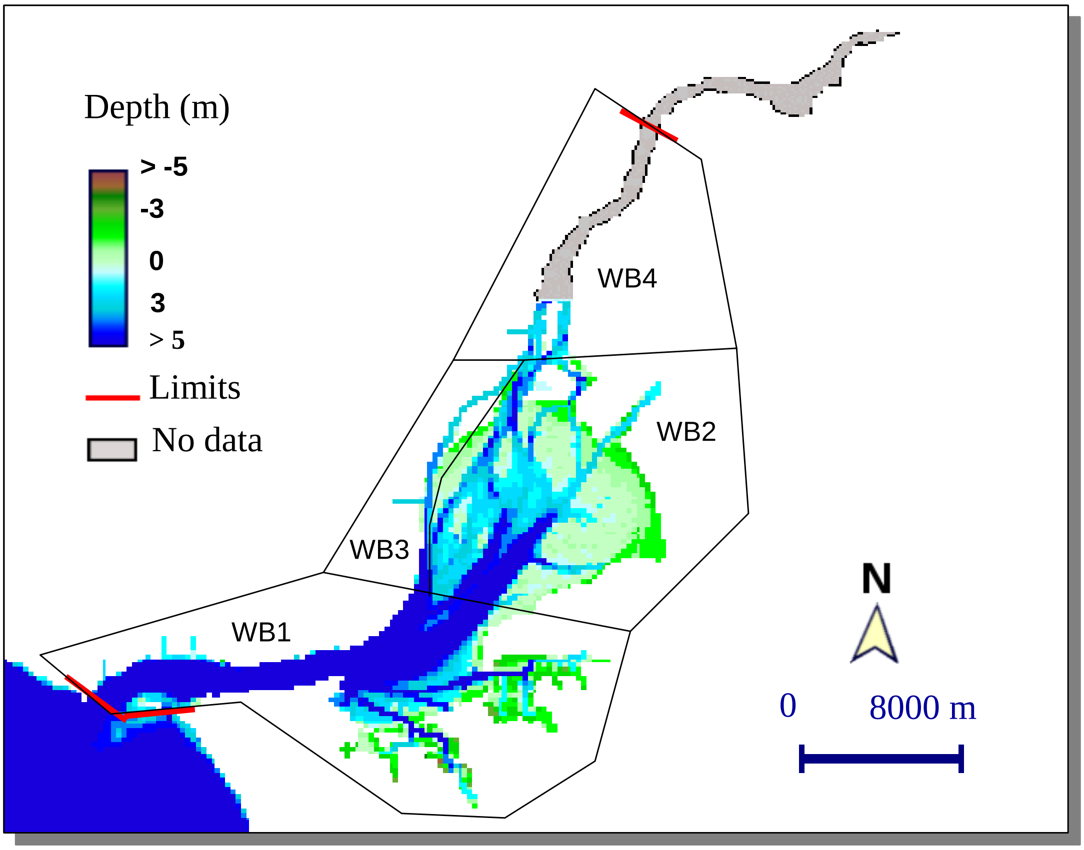


Figure 24 - Water bodies for the Sado estuary

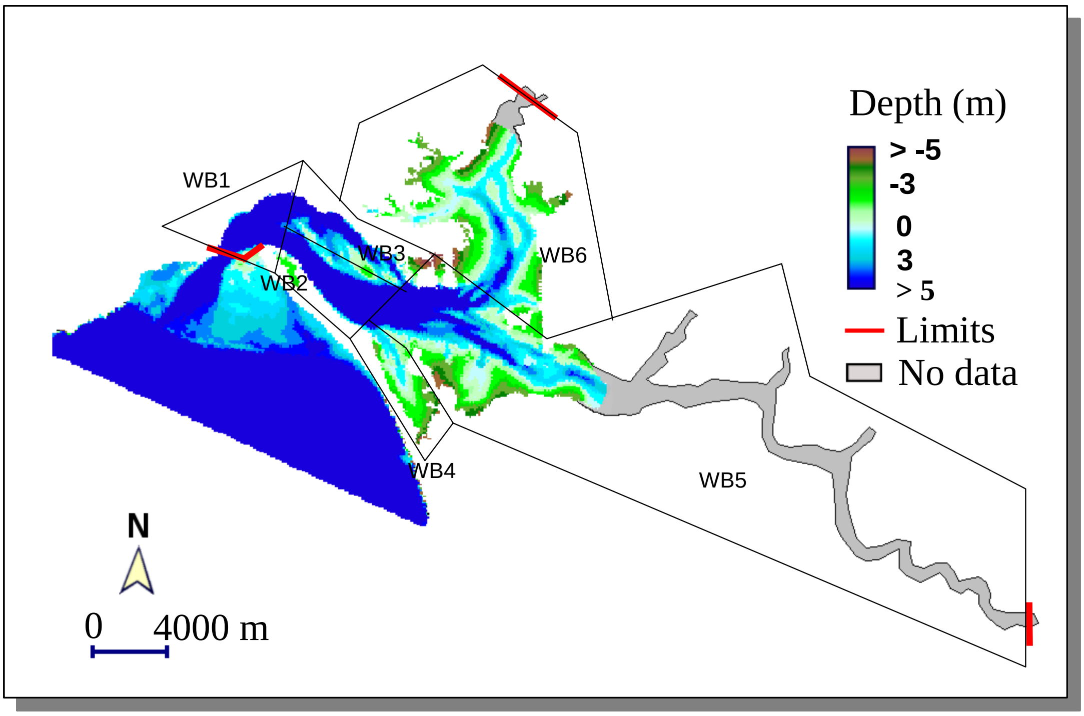


Figure 25 - Water bodies for the Mira estuary

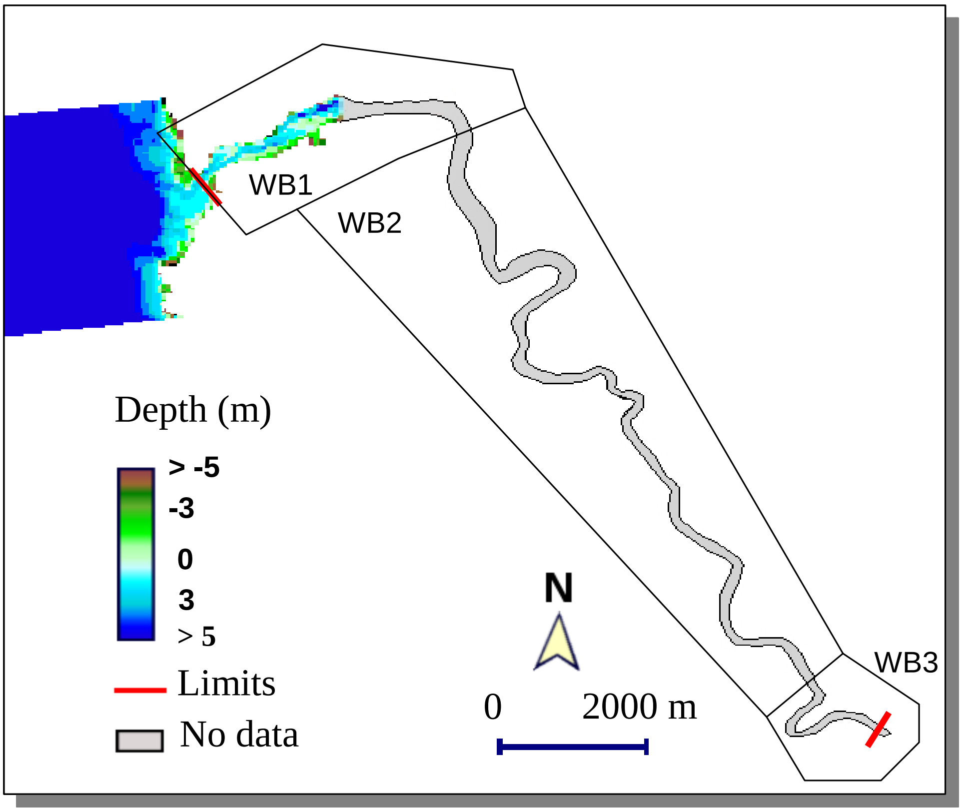


Figure 26 - Water bodies for the Ria Formosa

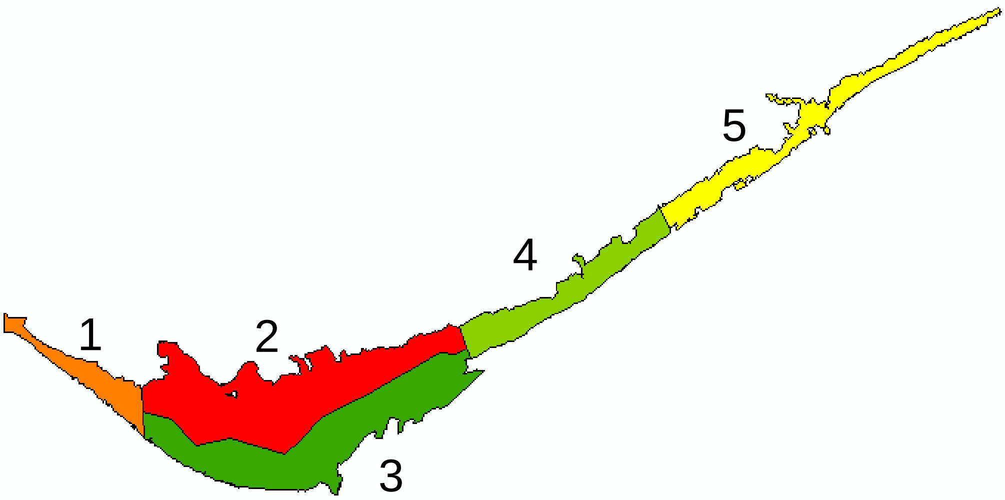
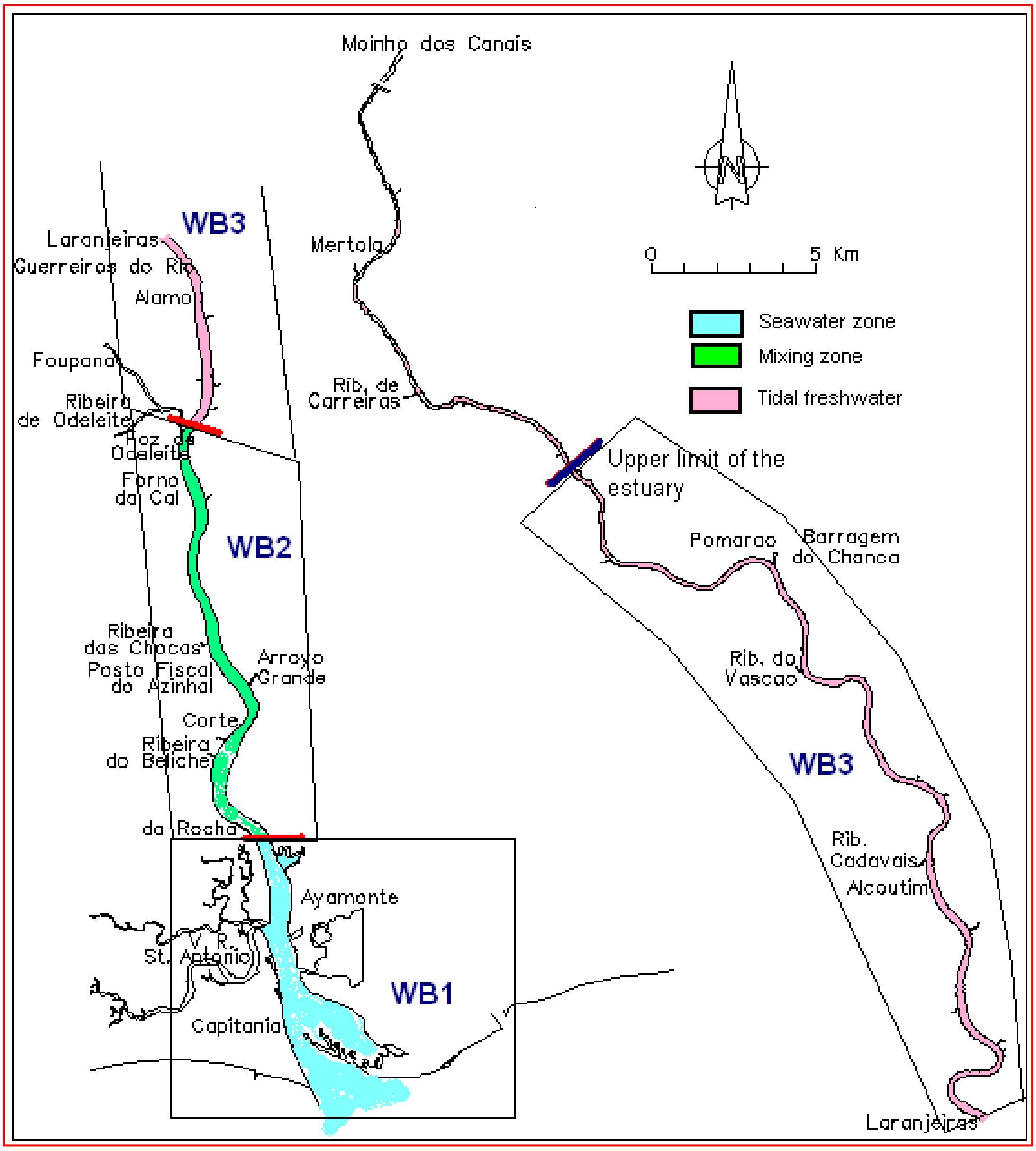


Figure 27 - Water bodies for the Guadiana estuary



CONCLUSIONS

An approach for the division of transitional and coastal waters in Portugal into water bodies for management and monitoring purposes was developed by a working group drawn from the MONAE team, and has been outlined in this document. Two distinct methodologies were used: for the definition of *Open Coastal Water Bodies* literature results were used, and for *Transitional and Restricted Coastal Water Bodies*, a bottom-up data analysis approach was taken.

Figure 28 - Summary of water bodies defined for transitional and coastal waters in Portugal

Types	Water category	Systems	Nº of water bodies
A1 – Mesotidal stratified estuary	Transitional	Minho estuary Lima estuary Douro estuary Leça estuary[3]	5 3 3 -
A2 – Mesotidal well-mixed estuary	Transitional	Ria de Aveiro Mondego estuary Tagus estuary Sado estuary Mira estuary Arade estuary Guadiana estuary	5 3 4 6 3 1 3
A3 – Mesotidal semi-enclosed lagoon	Coastal	Óbidos lagoon Albufeira lagoon St. André lagoon	2 1 1
A4 – Mesotidal shallow lagoon	Coastal	Ria Formosa Ria de Alvor	5 1
A5 – Mesotidal exposed Atlantic coast	Coastal	Open coast	6
A6 – Mesotidal moderately exposed Atlantic coast	Coastal	Open coast	4
A7 – Mesotidal sheltered Atlantic coast	Coastal	Open coast	4
Total			60

There are common points to both methodologies, since in the two cases natural factors such as salinity or morphology are combined with the human dimension, using the significant pressures and/or key elements of state.

The application of these methodologies has resulted in the definition of 60 transitional and coastal water bodies for Portugal, which are detailed in Figure 28.

KEY REFERENCES

Alexander, R.B., Johnes, P.J., Boyer, E.B., & Smith, R.A., 2002. A comparison of methods for estimating the riverine export of N from large watersheds. Biogeochemistry, 57: 295-339.

Alexander, R.B., R.A. Smith, G.E. Schwarz, S.D. Preston, J.W. Brakebill, R. Srinivasan and P. Pacheco. 2001. Atmospheric nitrogen flux from the watershed of

[3] The Leça estuary was excluded, since it is classified as an artificial structure (Bettencourt et al, 2003).

major estuaries of the United States: An application of the SPARROW watershed model. In: Nitrogen Loading in Coastal Water Bodies: An Atmospheric Perspective. R.A. Valigura, R.B. Alexander, M.S. Castro, T.P. Meyers, H.W. Paerl, P.E. Stacey, and R.E. Turner (eds). Coastal and Estuarine Studies. pp.119- 170. American Geophysical Union, Washington., D.C.

Alvera-Azcarate, A., Ferreira, J.G., & Nunes, J.P., 2003. Modelling eutrophication in mesotidal and macrotidal estuaries. The role of intertidal seaweeds. Est. Coast. and Shelf Sci., 57(4): 715-724.

Barbieri, P., Adami, G., Predonzani, S., Reisenhofer, E. & Massart, D.L., 1999. Survey of environmental complex systems: pattern recognition of physico-chemical data describing coastal water quality in the Gulf of Trieste. J. Environ. Monit., 1, 69-74.

Bettencourt, A., Bricker, S.B., Ferreira, J.G., Franco, A., Marques, J.C., Melo, J.J., Nobre, A., Ramos, L., Reis, C.S., Salas, F., Silva, M.C., Simas, T., & Wolff, W.J., 2003. Typology and Reference Conditions for Portuguese Transitional and Coastal Waters. Development of guidelines for the application of the European Union Water Framework Directive. INAG/IMAR, 2003.

Bricker, S.B., Clement, C.G., Pirhalla, D.E., Orlando, S.P., & Farrow, D.R.G., 1999. National Estuarine Eutrophication Assessment. Effects of Nutrient Enrichment in the Nation's Estuaries. NOAA-NOS Special Projects Office, Silver Spring.

Bricker, S.B., J.G. Ferreira, & T. Simas, 2003. An Integrated Methodology for Assessment of Estuarine Trophic Status. Ecological Modelling, 169(1), 39-60.

Cameron, W.M. & Pritchard, D.W., 1963. Estuaries. In The Sea Ed. M.N.Hill, Vol. 2, Wiley, New York, 306-324.

Câmara, A.S., Silva, M.C., Ramos, L., & Gomes Ferreira, J., 1987. TEJO1 - An interactive program for the division of estuaries into homogeneous areas. Water Sci. & Tech., 19, p. 43-51.

Cardoso da Silva, M. & Carmona Rodrigues, A., 2004. Environmental indicators as tools for the management of estuaries – Methodology and case study of the Tejo estuary. J. Coastal Conservation, 10, 13-24.

Cloern, J.E., 1982. Does the benthos control phytoplankton biomass in South San Francisco Bay? Mar. Ecol. Prog. Ser., 9: 191-202.

Common Implementation Strategy (CIS), 2003. Monitoring under the Water Framework Directive. Guidance Document nº 7. Working Group 2.7. 153 p.

Dobson, J., Gardner, M., Miller, B., Jessep, M., & Toft, R., 1999. An approach to the assessment of the quality of environmental monitoring data. J. Environ. Monit., 1, 91-95.

European Community, 2000. Directive of the European Parliament and of the Council 2000/60/EC, establishing a Framework forCommunity Action in the Field of Water Policy. 62 p.

Fairbridge, R.W., 1980. The estuary: its definition and geodynamic cycle. In Chemistry and Biogeochemistry of Estuaries Eds E Olausson & I Cato, Wiley, New York, 1-35.

Ferreira, J.G., Simas, T., Nobre, A., Silva, M.C., Schifferegger, K., & Lencart-Silva, J., 2003. Identification of Sensitive Areas and Vulnerable Zones In Transitional and Coastal Portuguese Systems. Application of the United States National Estuarine Eutrophication Assessment to the Minho, Lima, Douro, Ria de Aveiro, Mondego, Tagus, Sado, Mira, Ria Formosa and Guadiana systems. INAG/IMAR, 2003.

Hansen, D.V., & Rattray, M. Jr., 1966. New dimensions in estuarine classification. Limnol. Oceanog. 11, 319-326.

Jay, D.A., & Smith, J.D., 1988. Residual circulation in and classification of shallow stratified estuaries. In Physical Processes in Estuaries. Eds. J. Dronkers & W. Van Leussen. Springer-Verlag. Berlin, 21-41.

Ketchum, B.H., 1954. Relation between circulation and planktonic populations in estuaries. Ecology, 35: 191-200.

Kuo, W.L., Steenhuis, T.S., McCulloch, C.E., Mohler, C.L., Weinstein, D., DeGloria, S., & Swaney, D.P., 1999. Effect of grid size on runoff and soil moisture in a GIS-based, variable-source-area hydrology model. Water Resources Res., 35: 3419-3428.

Lee, Kuang-Yao, Fisher, T.R., & Rochelle-Newall, E.P., 2001. Modeling the hydrochemistry of the Choptank River basin using GWLF and Arc/Info: 2. Model validation and application. Biogeochemistry, 56: 311-348.

Lucas, L.V., Koseff, J.R., Monismith, S.G., Cloern, J.E., & Thompson, J.K., 1999. Processes governing phytoplankton blooms in estuaries. II: The role of horizontal transport. Mar. Ecol. Prog. Ser., 187: 17-30.

MacDonald, D.D., Carr, S.R., Calder, F.D., Long, E.D., & Ingersoll, C.G., 1996. Development and evaluation of sediment quality guidelines for Florida coastal waters. Ecotoxicology, 5:253-578.

May, C.L., Koseff, J.R., Lucas, L.V., Cloern, J.E., & Schoellhamer, D.H., 2003. Effects of spatial and temporal variability of turbidity on phytoplankton blooms. Mar. Ecol. Prog. Ser., 254: 111-128.

Oey, L-Y, 1984. On steady salinity distribution and circulation in partially mixed and well mixed estuaries. J. Phys. Oceanogr. 14, 629-645.

Prandle, D., 1985. On salinity regimes and the vertical structure of residual flows in narrow tidal estuaries. Est. Coast. Shelf Sci. 20, 615-635.

Pritchard, D.W., 1952. Salinity distribution and circulation in the Chesapeake Bay estuaries system. J. Mar. Res. 11, 106-123.

Pritchard, D.W., 1955. Estuarine circulation patterns. Proc. Am. Soc. Civ. Eng. 81. No. 717.

Smith, R.A., Schwarz, G.E., Alexander, R.B. 1997. Spatially Referenced Regressions on Watershed Attributes (SPARROW): Regional Interpretation of Water Quality Monitoring Data. Regional interpretation of water-quality monitoring data. Water Resour. Res. 33 (12), 2781–2798.

Tett, P., Gilpin, L., Svendsen, H., Erlandsson, C.P., Larsson, U., Kratzer, S., Fouilland, E., Janzen, C., Lee, J., Grenz, C., Newton, A., Ferreira, J.G., Fernandes, T., & Scory, S., 2003. Eutrophication and some European waters of restricted exchange. Cont. Shelf Res. 23: 1635-1671.

Valiela, I., Collins, G., Kremer, J., Lajtha, K., Geist, M., Seely, B.,, Brawley, J., & Sham, C.-H., 1997. Nitrogen Loading from coastal watersheds to receiving estuaries: New method and application. Ecological Applications 7:358–380.

Valiela, I., Mazzilli, S., Bowen, J.L., Kroeger, K.D., Cole, M.L., Tomasky, G., & Isaji, T., 2004. ELM an estuarine nitrogen loading model: Formulation, verification of predicted concentrations of dissolved inorganic nitrogen. Water, Air, and Soil Pollution. Water, Air, and Soil Pollution, Vol. 157, pp. 365-391.

Vincent, C., Heinrich, H., Edwards, A., Nygaard, K., & Haythornthwaite, J., 2003. Guidance on typology, classification and reference conditions for transitional and coastal waters. European Commission, report of CIS WG2.4 (COAST). 119 p.